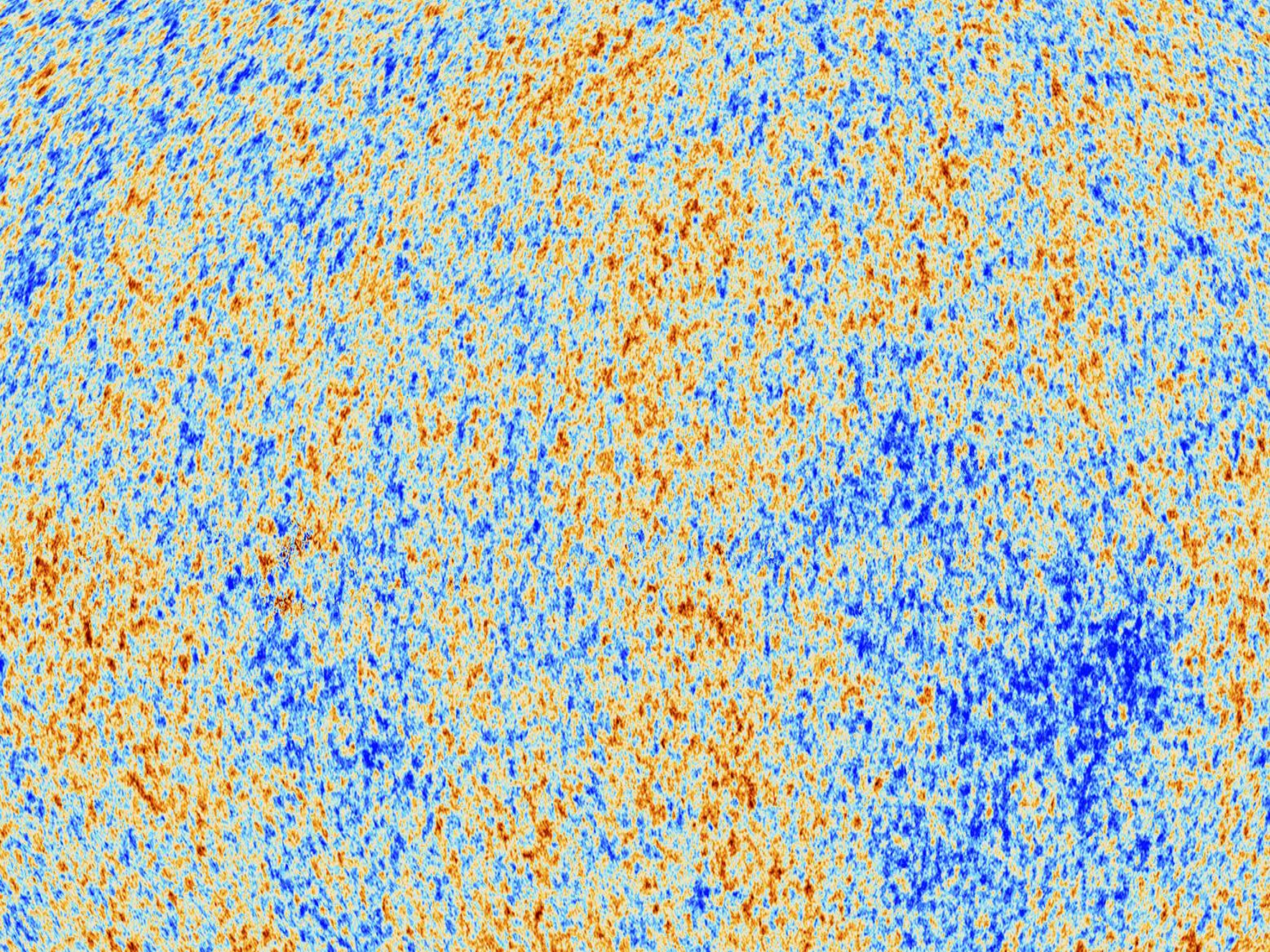
Inflationary gravitational waves: a window on ultraviolet physics

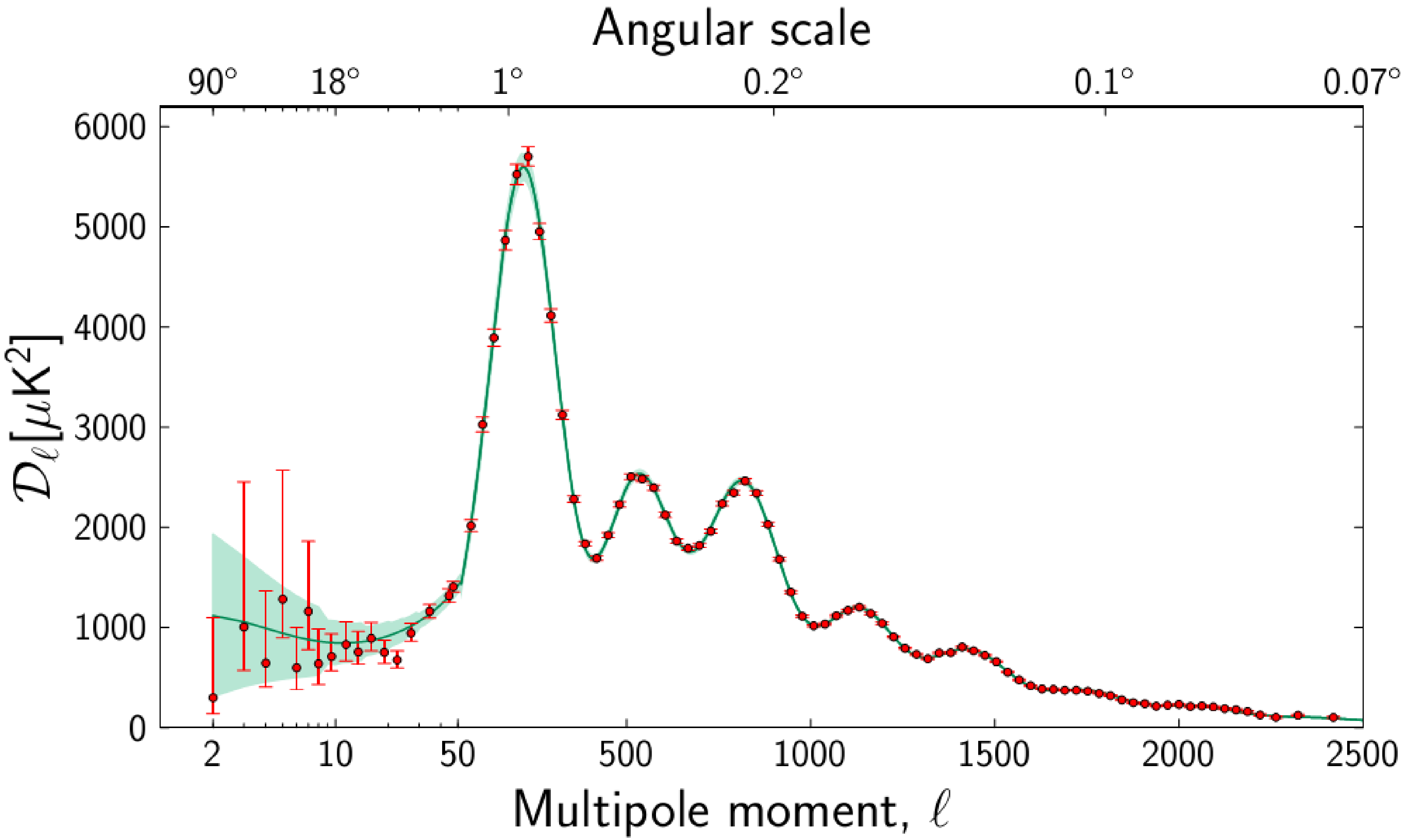
Liam McAllister
Cornell

Snowmass 2013, Minneapolis

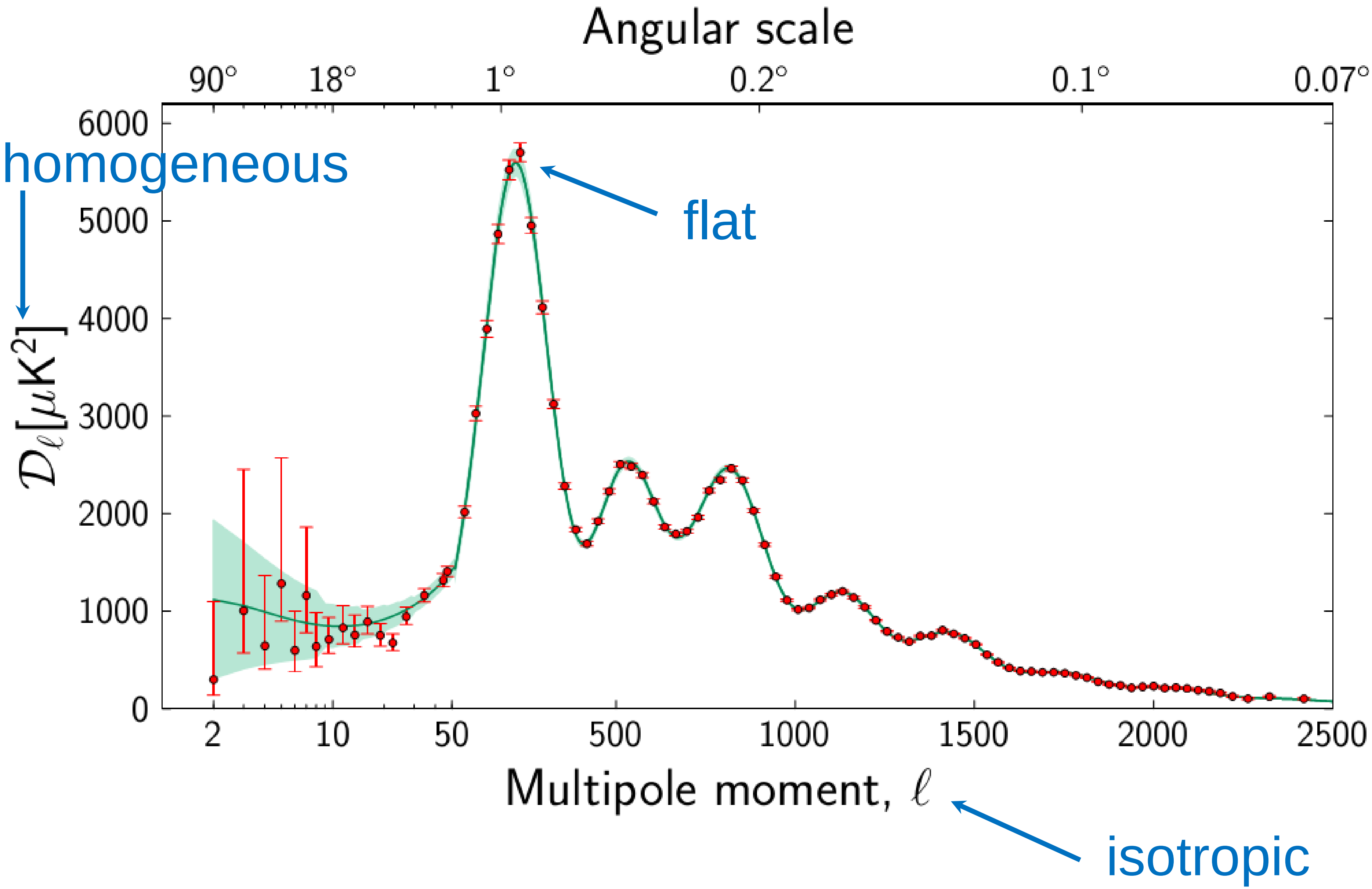
July 31, 2013



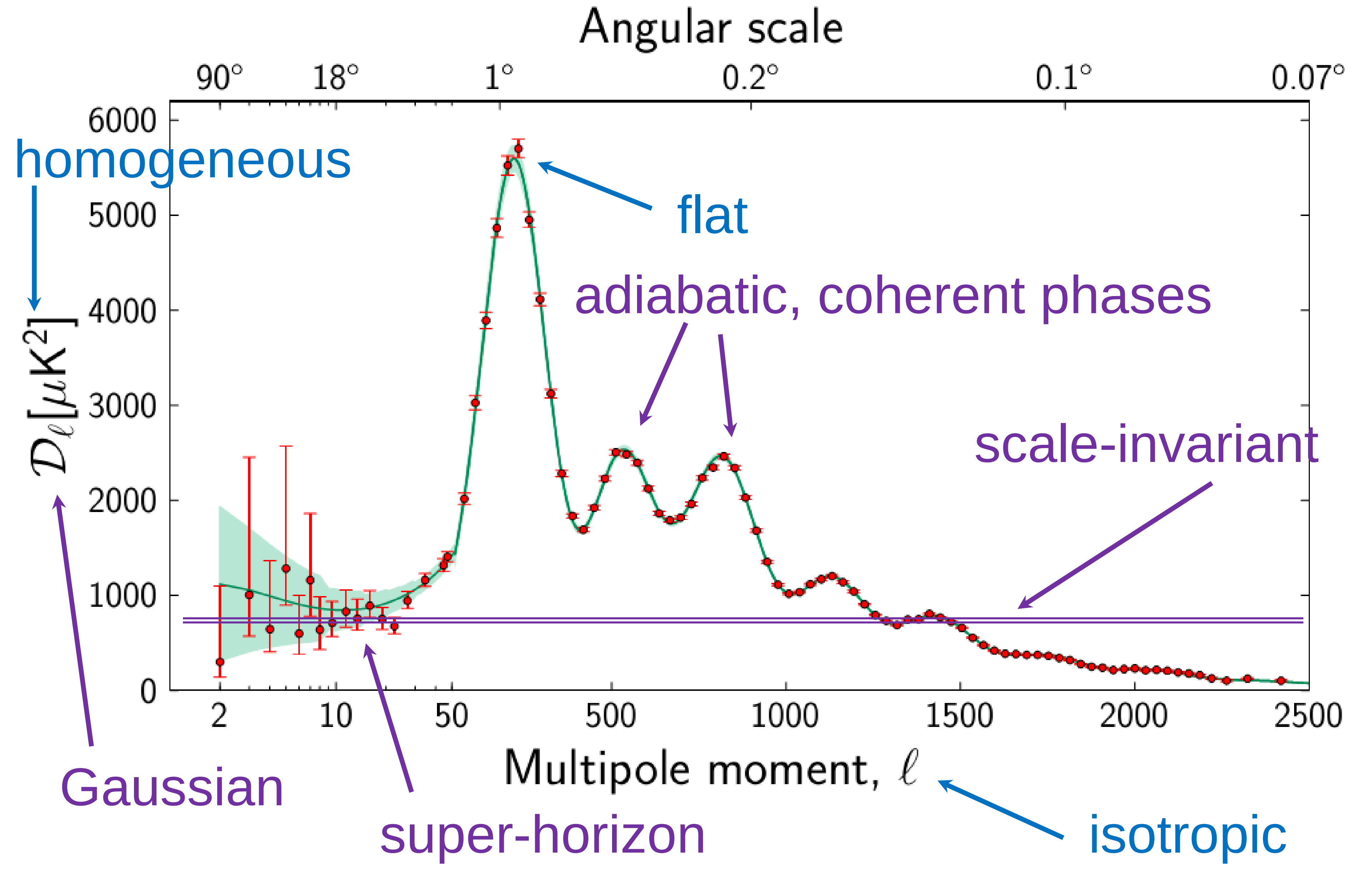
Planck 2013 CMB power spectrum



Planck 2013 CMB power spectrum



Planck 2013 CMB power spectrum



Inflation and Planck-scale physics.

- The evidence for inflation is compelling, but phenomenological models of inflation in effective field theory are sensitive to Planck-scale physics.
- Inflationary dynamics is controlled by Planck-suppressed contributions to the effective Lagrangian.

Inflation and Planck-scale physics.

- Inflationary dynamics is controlled by Planck-suppressed contributions to the effective Lagrangian.
  - The ultraviolet completion of gravity should furnish new d.o.f. with mass Λ at or below the Planck scale.
  - Integrating out these d.o.f. yields Λ-suppressed terms in the EFT.
  - For $\mathcal{O}(1)$ couplings of the inflaton to these d.o.f., operators with dimension $\Delta \leq 6$ control the dynamics, even for $\Lambda = M_p$.

$$\mathcal{L}_{\rm eff}[\phi] = \mathcal{L}_{\ell}[\phi] + \sum_{i=1}^{\infty}\left(\frac{c_i}{\Lambda^{2i}}\phi^{4+2i} + \frac{d_i}{\Lambda^{2i}}(\partial\phi)^2\phi^{2i} + \frac{e_i}{\Lambda^{4i}}(\partial\phi)^{2(i+1)} + \cdots\right)$$

- Thus, some properties of inflation are dictated by the ultraviolet completion of gravity.
- This is a burden for the model-builder, but also an invaluable window on ultraviolet physics.

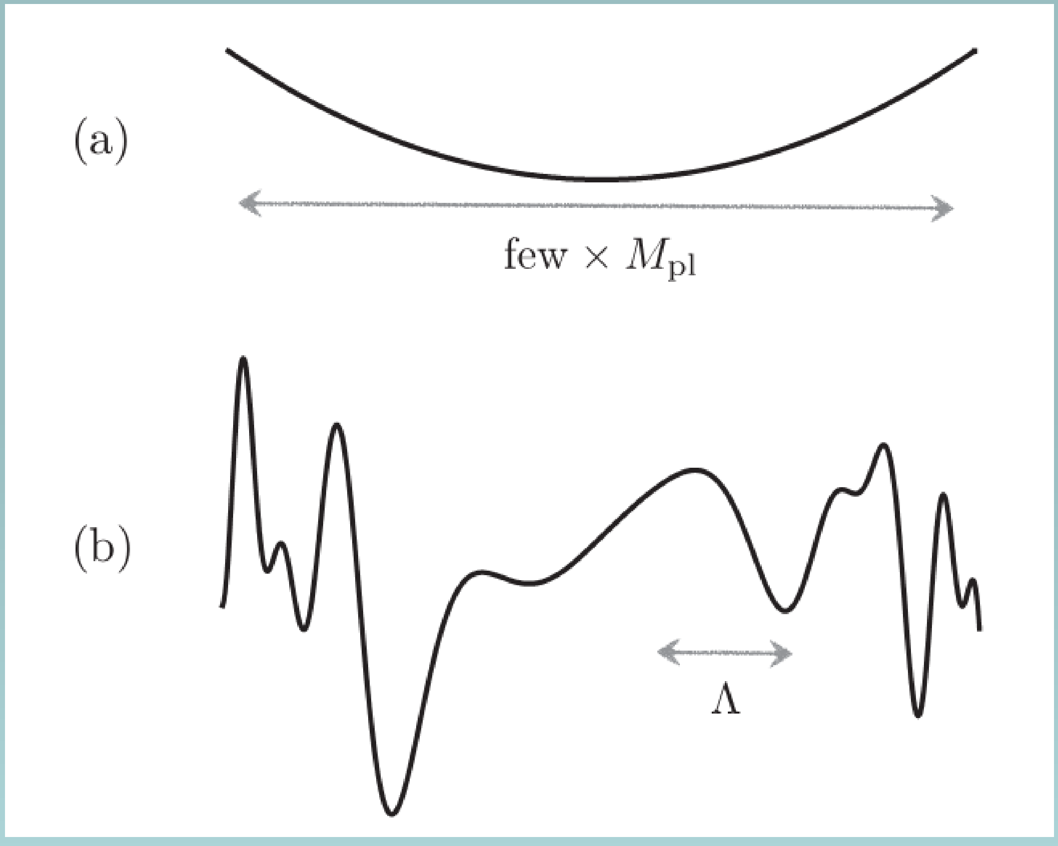
Inflation and Planck-scale physics.

- Sensitivity to operators with $\Delta \leq 6$ is universal. In one important class of models, 'large-field inflation', the sensitivity is vastly increased:
- 'Large-field inflation' $\Leftrightarrow \Delta\phi > M_p$. But $\Lambda \leq M_p$.
  So, naively, an infinite series of operators contributes:

$$\mathcal{L}_{\rm eff}[\phi] = \mathcal{L}_\ell[\phi] + \sum_{i=1}^{\infty}\left(\frac{c_i}{\Lambda^{2i}}\phi^{4+2i} + \frac{d_i}{\Lambda^{2i}}(\partial\phi)^2\phi^{2i} + \frac{e_i}{\Lambda^{4i}}(\partial\phi)^{2(i+1)} + \cdots\right)$$

- Detectable inflationary gravitational waves are possible only in large-field inflation. Thus, detecting primordial tensors would reveal a stage of cosmic history in which the details of quantum gravity are essential.

Large-field inflation



$$\mathcal{L}_{\mathrm{eff}}[\phi] = \mathcal{L}_{\ell}[\phi] + \sum_{i=1}^{\infty}\left(\frac{c_i}{\Lambda^{2i}}\phi^{4+2i} + \frac{d_i}{\Lambda^{2i}}(\partial\phi)^2\phi^{2i} + \frac{e_i}{\Lambda^{4i}}(\partial\phi)^{2(i+1)} + \cdots\right)$$

Lyth Bound

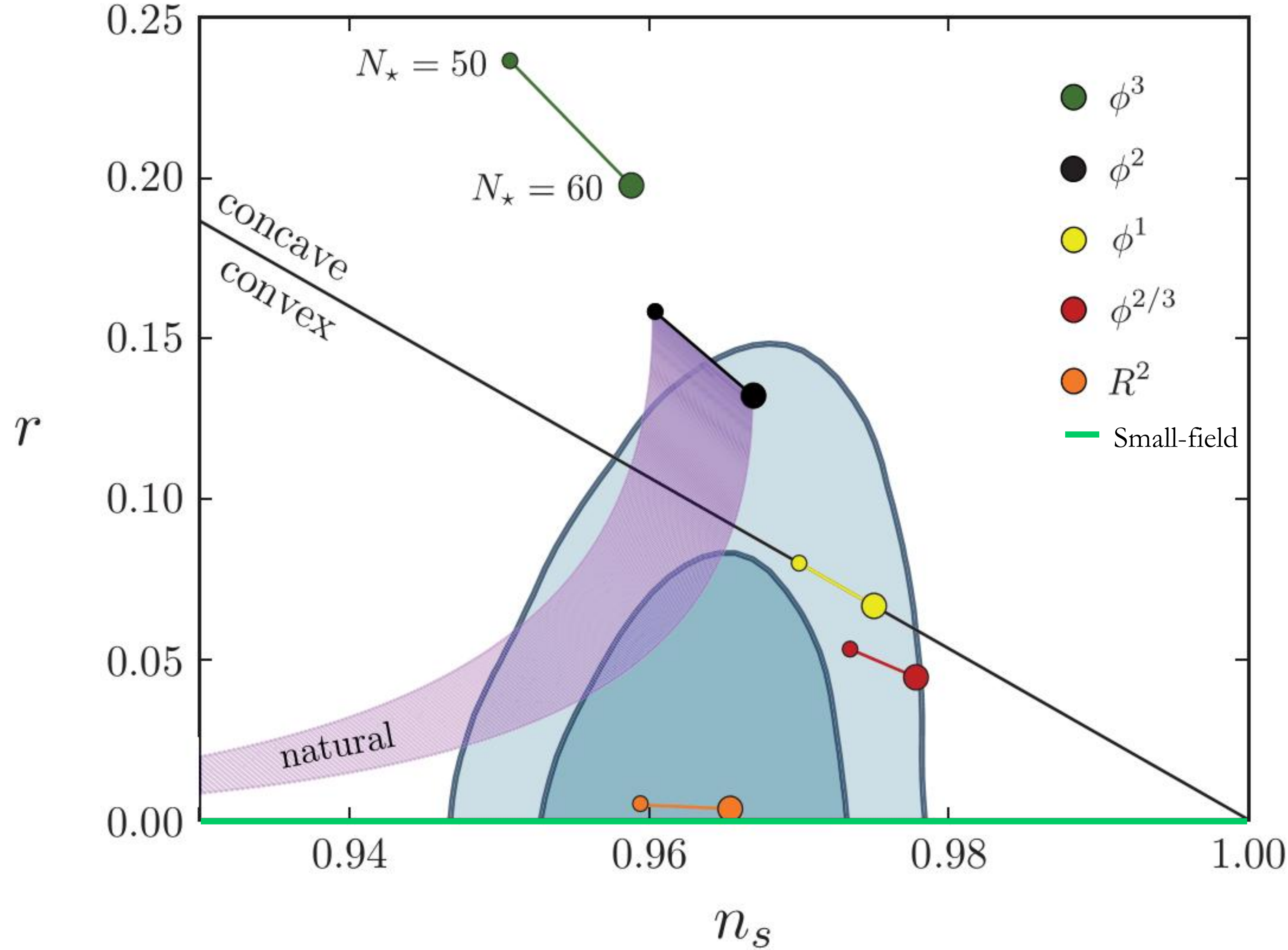
$$r \equiv \frac{\Delta_h^2}{\Delta_\mathcal{R}^2} \qquad \Delta_\mathcal{R}^2 = \frac{1}{24\pi^2}\frac{1}{\epsilon}\frac{V}{M_\mathrm{pl}^4} \qquad \text{and} \qquad \Delta_h^2 = \frac{2}{3\pi^2}\frac{V}{M_\mathrm{pl}^4}$$

$$\epsilon = \frac{\frac{1}{2}\dot{\phi}^2}{M_\mathrm{pl}^2 H^2} \qquad \mathrm{d}N \equiv H\mathrm{d}t \qquad r = 8\left(\frac{1}{M_\mathrm{pl}}\frac{\mathrm{d}\phi}{\mathrm{d}N}\right)^2$$

$$\frac{\Delta\phi}{M_\mathrm{pl}} = \int_0^{N_\star} \mathrm{d}N \sqrt{\frac{r(N)}{8}}$$

$$\boxed{\frac{\Delta\phi}{M_\mathrm{pl}} \approx \mathcal{O}(1) \times \left(\frac{r}{0.01}\right)^{1/2}}$$

Lyth 96



0.25
0.20
0.15
0.10
0.05
0.00
0.94
0.96
0.98
1.00
r
n_s
$N_\star = 50$
$N_\star = 60$
concave
convex
natural
ϕ^3
ϕ^2
ϕ^1
$\phi^{2/3}$
R^2
Small-field

Symmetries and large-field inflation

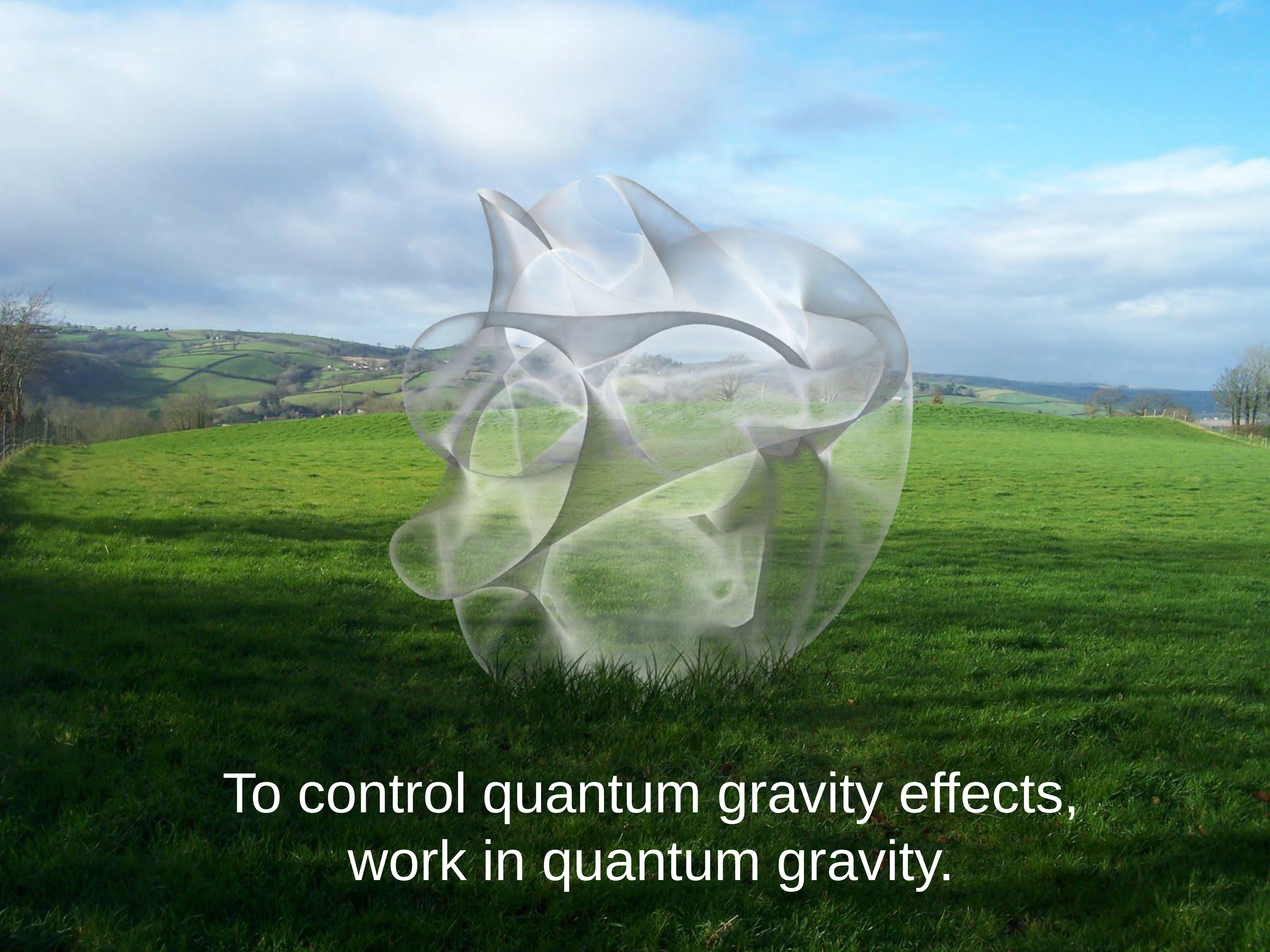
Large-field inflation is interesting and important, because it is particularly sensitive to ultraviolet physics, and because it makes testable predictions.

To realize large field inflation, we should find a symmetry that protects the inflaton over a super-Planckian range.

In EFT, one can find suitable symmetries: e.g. Peccei-Quinn shift symmetry (‘natural inflation’) **Freese, Frieman, Olinto 90**

The question is whether a given EFT symmetry admits an ultraviolet completion (in quantum gravity).

This is highly nontrivial! String theory very plausibly contains appropriate symmetries protecting large-field inflation, but in all cases the UV completion entails additional structure, and sometimes a significant modification of the EFT mechanism.



To control quantum gravity effects,
work in quantum gravity.

Axion inflation

Axion shift symmetry, valid perturbatively, is broken by nonperturbative effects, which generate a periodic potential for the axion:

$$\Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

Freese, Frieman, Olinto 90

For $f>4M_p$, the model is consistent with Planck.

String theory contains many axions enjoying all-orders shift symmetries. But $f>M_p$ does not seem attainable in controllable solutions. Banks, Dine, Fox, Gorbatov 03

Nevertheless, large-field models protected by symmetries with f<Mp have been found in string theory. Their signatures are distinctive.

Kim, Nilles, Peloso 04
Dimopoulos, Kachru, McGreevy, Wacker 05
Grimm 07
Silverstein, Westphal 08
L.M., Silverstein, Westphal 08
Kaloper, Sorbo 08
Flauger, L.M., Pajer, Westphal, Xu 09
Berg, Pajer, Sjors 09

Axion monodromy

A string theory realization of chaotic inflation.

Potential is asymptotically linear, with large field range, and has modulations from nonperturbative symmetry breaking.

$$V(\phi) = \mu^3\phi + \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

L.M., Silverstein, Westphal 08

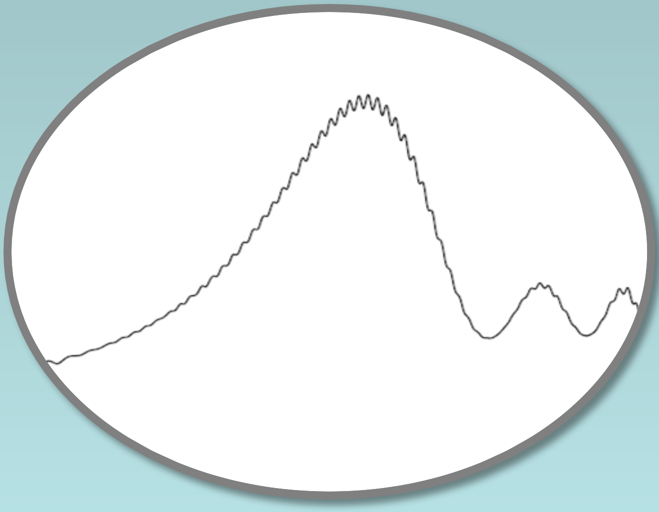
Prediction: r=0.07

Correlated signature:

modulations of spectrum

and bispectrum

Flauger, L.M., Pajer, Westphal, Xu 09

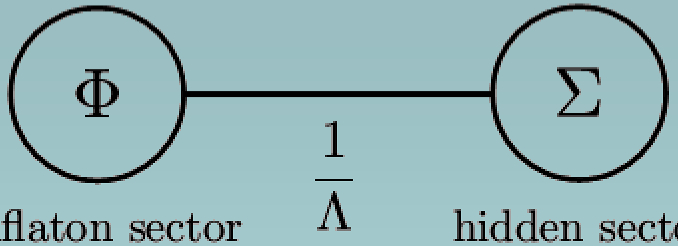


Limits on light hidden sector fields

- Can we constrain light hidden sector fields using observations of the CMB T (and B) anisotropies?
- Method: write general EFT coupling to hidden sector; use Planck limit on non-Gaussianity, $f_{\rm NL}^{\rm local} = 2.7 \pm 5.8$

Green, Lewandowski, Silverstein, Senatore, Zaldarriaga 13
Assassi, Baumann, Green, L.M. 13

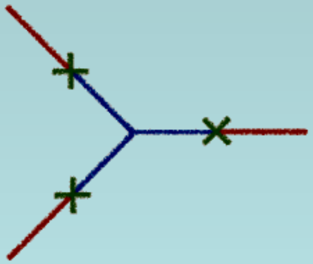
as a precision constraint.



$$\Lambda \gtrsim 0.5 \left(\frac{|\mu|}{H}\right)^{1/3} \left(\frac{r}{0.01}\right)^{1/2} M_{\rm pl}$$

$$\mathcal{L}_\Sigma \supset -\mu\Sigma^3$$

$$\Lambda > 10^5 H = \sqrt{\frac{r}{0.01}}\, M_{\rm pl}$$



Conclusions

- Inflation is sensitive to Planck-scale physics, and in large-field inflation this sensitivity is extreme.
- Detection of inflationary gravitational waves would tell us
  - the scale of inflation: $V = (r/.01)^{1/4} \times 10^{16}$ GeV
  - that a symmetry structure in quantum gravity ensures that the action varies slowly over super-Planckian distances
  - that light hidden sector scalars must be sequestered from us ($\Lambda > M_p$) or sequestered from inflation (cubic coupling << H).
- Non-detection would tell us much less.
- The nature of the window on Planck scale physics has been sharpened by the study of inflation in string theory.
- Much work remains before we can understand what sort of inflationary dynamics is generic in string theory. So it would be premature to claim clear expectations from string theory.

Thank you!